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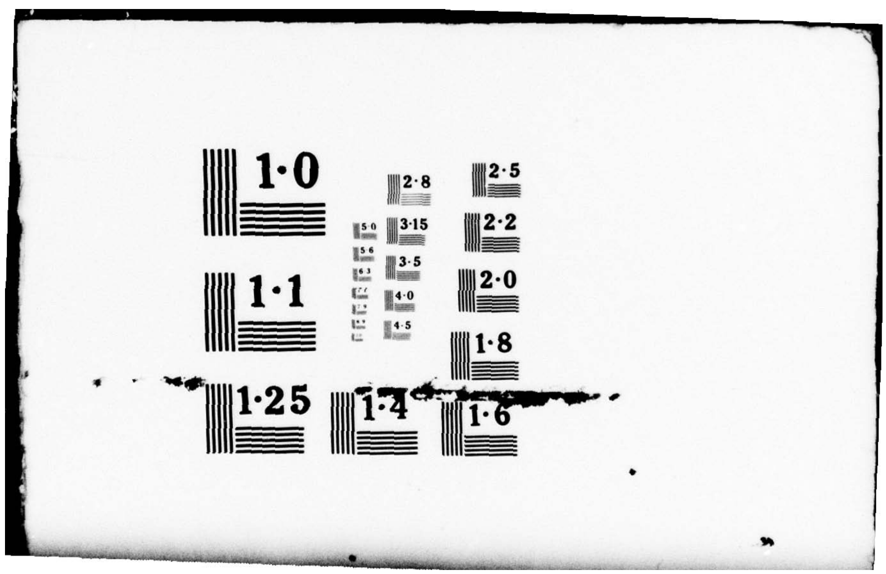
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INSTITUTE FOR ACOUSTICAL RESEARCH
MIAMI DIVISION PALISADES GEOPHYSICAL INSTITUTE

BEAR Buoy Study:

Internal Wave Mode Perturbations
Due to the Passage of a Mesoscale Feature

by

Kenneth L. Echternacht

IAR 78004

November 1978

Miami, Florida 33130

Institute for Acoustical Research
Miami Division of
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NOTE

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Abstract

This study examines, in detail, the effect of the passage of a meso-scale feature through an area normally under the influence of the Antilles Current. The study area lies approximately 40 km northeast of the island of Eleuthera, Bahamas. The analyses examine, in particular, changes in structure of the vertical displacements of the semi-diurnal tidal component of the internal wave field. The report also includes a description of the methodology used to compute the vertical displacements.

Acknowledgments

This work was supported by the Office of Naval Research under contract No. N00014-74-C-0229. The author wishes to acknowledge the following I.A.R. personnel for their support and help during the course of this study: Morton Kronengold, Director, Dr. William Jobst, Mr. James Doubek, and Ms. Martha Prohias.

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1.0 Introduction

The observations used in this and a previous study (Echternacht, 1978) were acquired over the period February through April 1976 using the BEAR Buoy System (BEAR acronymn for Bermuda Eleuthera Acoustics Range). The system comprised a semi-taut surface buoyed mooring system using a thermistor cable to measure ocean temperatures from near surface to a depth of approximately 1900 m. The experimental site was located approximately 40 Km northeast of the island of Eleuthera, Bahamas (Fig. 1) at 25°45'N, 76°17'W. The anchor position was located on the abyssal plain approximately 20 Km seaward of the base of the continental slope at a depth of 4797 m. Detailed descriptions of the system and components as well as data reduction and correction techniques used can be found in Echternacht (1976), Kronengold (1976), and Echternacht (1977).

The primary intent of the experiment was to provide data to be used to examine the amplitude and relative changes in amplitude of the internal tides along the Eleuthera shelf region. The previous report dealing with the observations presented the following (Echternacht, 1978).

1. An examination of the temperature time series at various depths from near surface to below the thermocline. The time series covered a 51 day period from 16 February through 6 April 1976.

2. A discussion of the depth and temporal changes of the observed profiles of static stability - Brunt-Väisälä.
3. A discussion of changes in the internal semi-diurnal tidal field over the period of record.
4. A qualitative discussion of the passage of a meso-scale feature through the area during the period of record.

The intent of this study is the following.

1. To present the method used to compute the vertical displacements for the (baroclinic) internal modes.
2. To examine in greater detail changes in the structure of the internal modes due to the influence of the observed meso-scale feature.

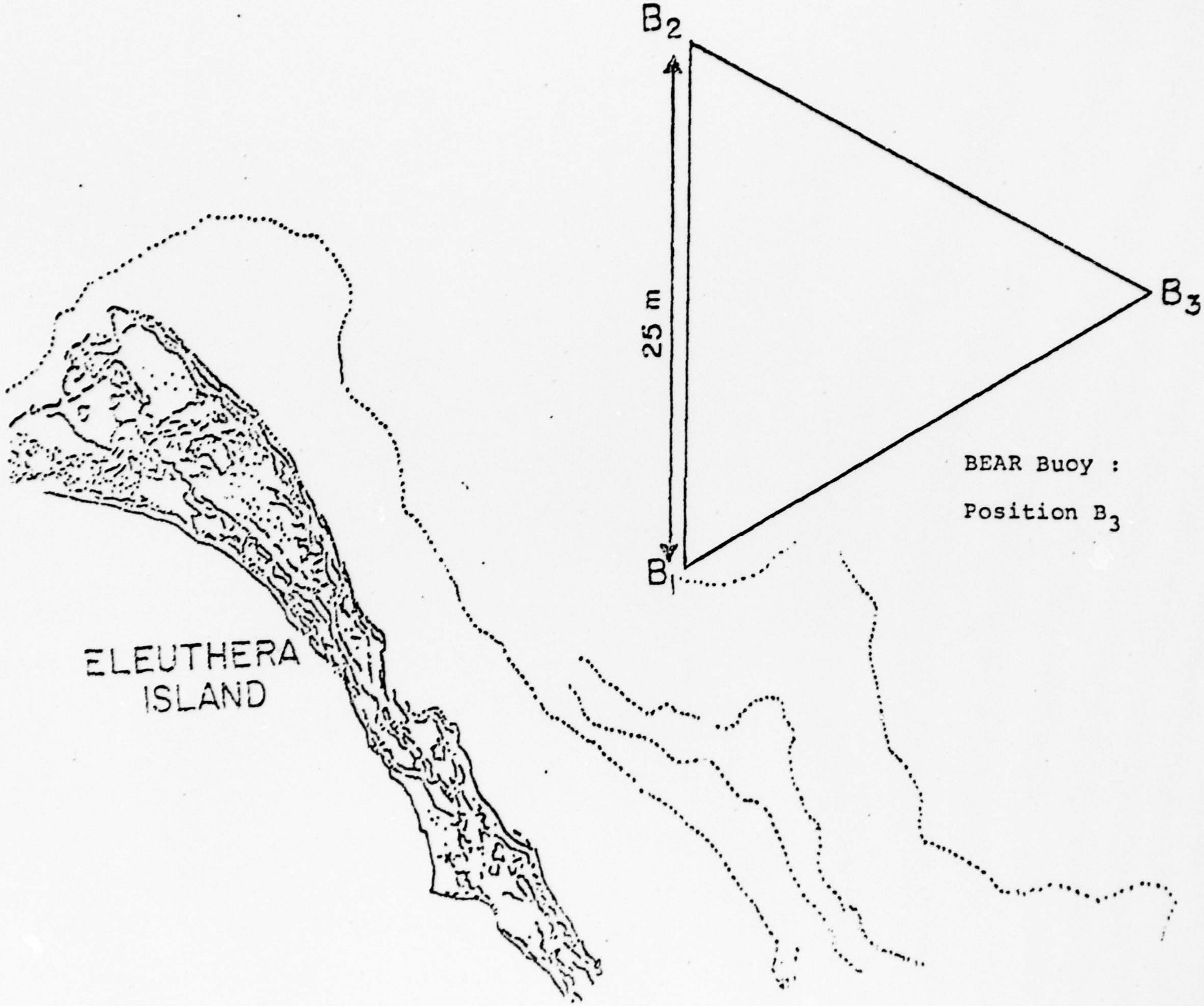


Fig. 1 The Study Area

2.0 Synopsis of Internal Wave Theory

The emphasis of this study is the examination of internal motions with frequency, σ, bounded by the local inertial and static stability frequencies; i.e., $f < \sigma < N$. In particular, this study examines the semi-diurnal tidal frequency, primarily, because internal **tidal** waves are commonly observed to be the most energetic, especially in the study region. The theory to be presented is intended, strictly, as a recapitulation of the established theory in this area.

In considering the above internal motions for the study area the basic equations of motion representative mid-latitudes are as follows.

$$\frac{\partial u}{\partial t} - f v = - \frac{\partial P}{\partial x} \tag{1}$$

$$\frac{\partial v}{\partial t} + f u = - \frac{\partial P}{\partial y} \tag{2}$$

and

$$\frac{\partial w}{\partial t} = - \frac{\partial P}{\partial z} + b \tag{3}$$

The coordinate system used is of standard notation; ie (x - east, v - north, and z - vertical downward with reference to the sea surface). The parameter b represents the fluctuation in buoyancy, p the departure from hydrostatic pressure, and f the Coriolis parameter

$$b = -g \frac{\rho - \overline{\rho}}{\overline{\rho}} \tag{4}$$

The bar represents the mean and g the acceleration due to gravity. It should be noted that the above (Eqs. 1-3) are the linearized, nondissipative equations of motion and assume an incompressible ocean. The latter assumption yields the following.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (5)$$

The buoyancy equation is

$$\frac{\partial b}{\partial t} + wN^2 = 0 \qquad (6)$$

where, N is the static stability or Brunt-Väisälä frequency. Typically, N is defined as follows (Phillips, 1966).

$$N^2 = -\frac{g}{\bar{\rho}}\frac{d\rho}{dz} - \left(\frac{g}{c}\right)^2 \qquad (7)$$

c is the speed of sound. For the study area N^2 is strongly depth dependent. In the water layer above the thermocline (<1000 m) the stability is influenced by variations in the Antilles Current, seasonal changes occurring in the mixed layer and perturbations due to the passage of mesoscale eddies embedded in the mean flow. Below thermocline depth the waters are approximately neutrally stable.

Of particular interest in the study of internal waves is the structure of the vertical displacement as a function of depth. The standard method used to compute the vertical displacements seeks wave solutions which assume simple harmonic motion in time ($e^{i\sigma t}$). After differentiation with respect to time Eqs. (3) and (6) are added together forming:

$$(N^2 - \sigma^2) w = -i\sigma \frac{\partial P}{\partial z} \tag{7}$$

Using an eigenfunction expansion which assumes that the variables are separable with respect to spatial dependency Eq (7) yields:

$$\frac{d^2 w}{d z^2} + k^2 \left(\frac{N^2 - \sigma^2}{\sigma^2 - f^2} \right) w = 0 \tag{8}$$

k^2 is an unknown eigenvalue, For a more complete discussion of the steps involved to arrive at Eq. (8) the reader should refer to Mooers (1975).

For this study Eq. (8) was solved numerically using N^2 profiles computed from environmental data. The numerical methodology used is treated in Section 4.0 of this report. The environmental data used for this study were presented in an earlier report (Echternacht, 1978).

3.0 The Data

The environmental data were presented and discussed in the previous report (Echternacht, 1978). To summarize, the temperature time series covered the 51.5 day period from 1200 LST Julian Day (JD) 46 through JD 97, 1976 (15 February - 6 April). The data are shown in Fig. 2. In the figure the axes are Julian Days (time) on the abscissa and temperature (^{o}c) on the ordinate. The same ordinate scaling was used for all data. Each temperature trace, comprised of 3-hourly values, represents the temperature which occurred at the corrected depth over the period of record. The sensor number appears to the right of each temperature trace. The corresponding corrected depths are given in Table 1. The obvious features are (1) the meso-scale feature covering approximately a 24 day period from the start of the record to JD 70, and (2) pronounced semi-diurnal oscillations.

In an attempt to qualitatively classify the meso-scale feature the data were compared with the Ring Criteria defined by Lai and Richardson (1977). From that comparison it was concluded that the observed feature was most likely the edge of an eddy traversing the study area (refer to Echternacht, 1978).

In examining the record (Fig. 2) it is obvious that the occurence of the meso-scale event introduces non-stationarity into the data. Thus the data were segmented into sections representative of different stages of meso-scale influence. The sectioning was as follows.

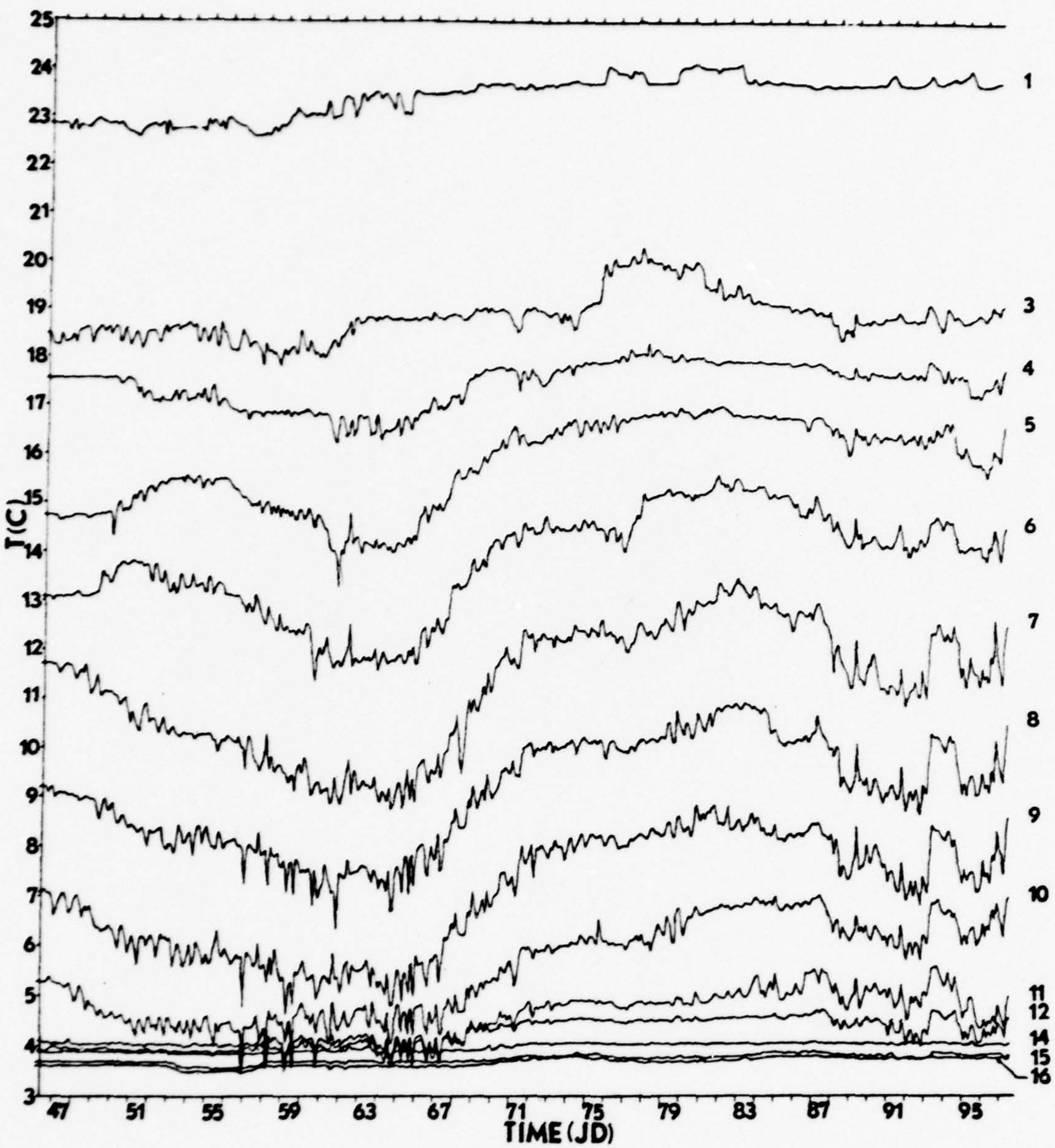


Fig. 2 The BEAR Buoy 3-hourly Temperature Time Series

1. Section 1 covering JD 47-57: period of onset of the meso-scale event.
2. Section 2 covering JD 57-69: period of greatest perturbing.
3. Section 3 covering JD 69-76: period of the passage of the event.
4. Section 4 covering JD 76-88: quiescent - no observable meso-scale feature.
5. Section 5 covering JD 88-97: minor perturbation in the record.

The above sectioning was used to study the above listed as static cases. To arrive at the data base for this study the temperature and N^2 profiles used in the previous analyses (Echternacht, 1978) were averaged. The averaged data and the profiles used for each average are given in Tables 1 and 2 for the temperature and N^2 data, respectively. Fig. 3 compares the average temperature profiles with the climatological mean for the region during the winter season. The meso-scale event had a decided cooling effect on the water column in the zone from approximately the base of the mixed layer to the thermocline. It should be noted that the Section 4 data (profiles 16-20) are nearly identical to the climatological mean.

The N^2 sections are presented in Fig. 4. The trace in the diagram is given for the quiescent period only. For period 4 the profile is typical for the winter case in the Eleuthera area: the shallow mixed layer stable zone, the stable layer centered in and around 600-700 m due to the

Depth (m)	Profile 1-5	6-11	12-15	16-20	21-25	Clim. Mean
22	22.8	23.2	23.7	23.8	23.7	22.3
250	18.5	18.6	19.1	19.5	18.8	19.0
350	17.3	16.8	17.8	18.0	17.6	17.8
450	15.1	14.6	16.4	16.8	16.3	16.6
550	13.3	12.3	14.3	15.1	14.3	15.2
650	10.6	9.5	12.0	12.8	11.7	13.0
750	8.4	7.6	9.8	10.4	9.5	10.4
850	6.1	5.6	7.7	8.4	7.7	8.2
950	4.6	4.5	5.8	6.6	6.3	6.7
1050	4.0	4.0	4.7	5.0	5.0	5.6
1150	3.9	4.0	4.5	4.5	4.4	4.9
1480	3.9	3.9	4.0	4.0	4.0	4.2
1650	3.7	3.7	3.8	3.8	3.8	4.1
1830	3.6	3.6	3.7	3.7	3.8	3.9

Table 1

Average Temperature Profile Data (^{o}C) and the Climatological Mean (^{o}C)

$N^2 \times 10^{-5}$

Depth	Profile 1-5	6-11	12-15	16-20	21-25
22	3.88	4.29	4.31	4.03	4.60
150	6.12	6.62	6.67	6.28	6.99
250	0.93	2.26	1.34	1.90	0.91
350	2.99	2.91	1.32	0.84	1.27
450	1.13	2.16	1.89	1.17	1.72
550	2.63	2.49	1.99	2.31	2.60
650	1.92	1.08	2.24	2.58	2.08
750	1.47	1.10	1.53	1.59	1.07
850	0.89	0.43	1.65	1.57	0.82
950	0.07		0.45	1.03	0.67
1050				0.28	0.33

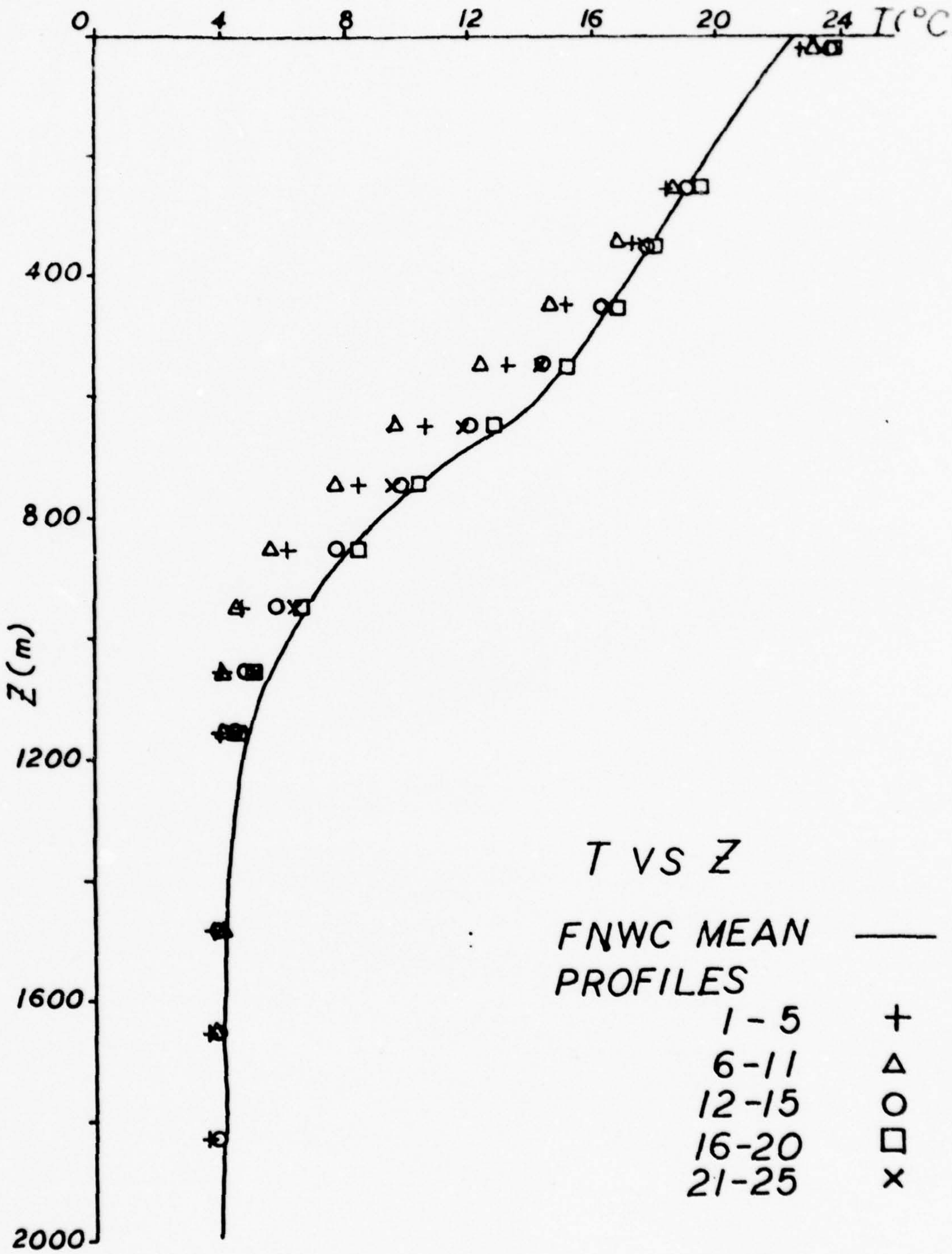
2000	1.0×10^{-6}
5000	1.0×10^{-8}

Table 2

Static Stability: N^2 (radians/sec)^2

Antilles Current, and near neutral stability at depths below the thermocline. For periods under the influence of the meso-scale feature (Sections 1-3) there exist noted perturbations in the N^2 profile. The most note-worthy are the formation of a secondary stable layer below the mixed layer zone and a decrease in stability in 600-700 m layer. The latter suggests a weakening of the effect of the Antilles Current by the introduction of the waters with different properties or at least differences in the vertical distribution of those properties.

The analyses to follow (Section 5.0) will present the effect of the meso-scale event on the structure of the vertical displacements of the semi-diurnal tidal component of the internal wave field. The next section will deal with the method used to numerical compute the vertical displacements.



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T(°C)
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T VS Z
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PROFILES
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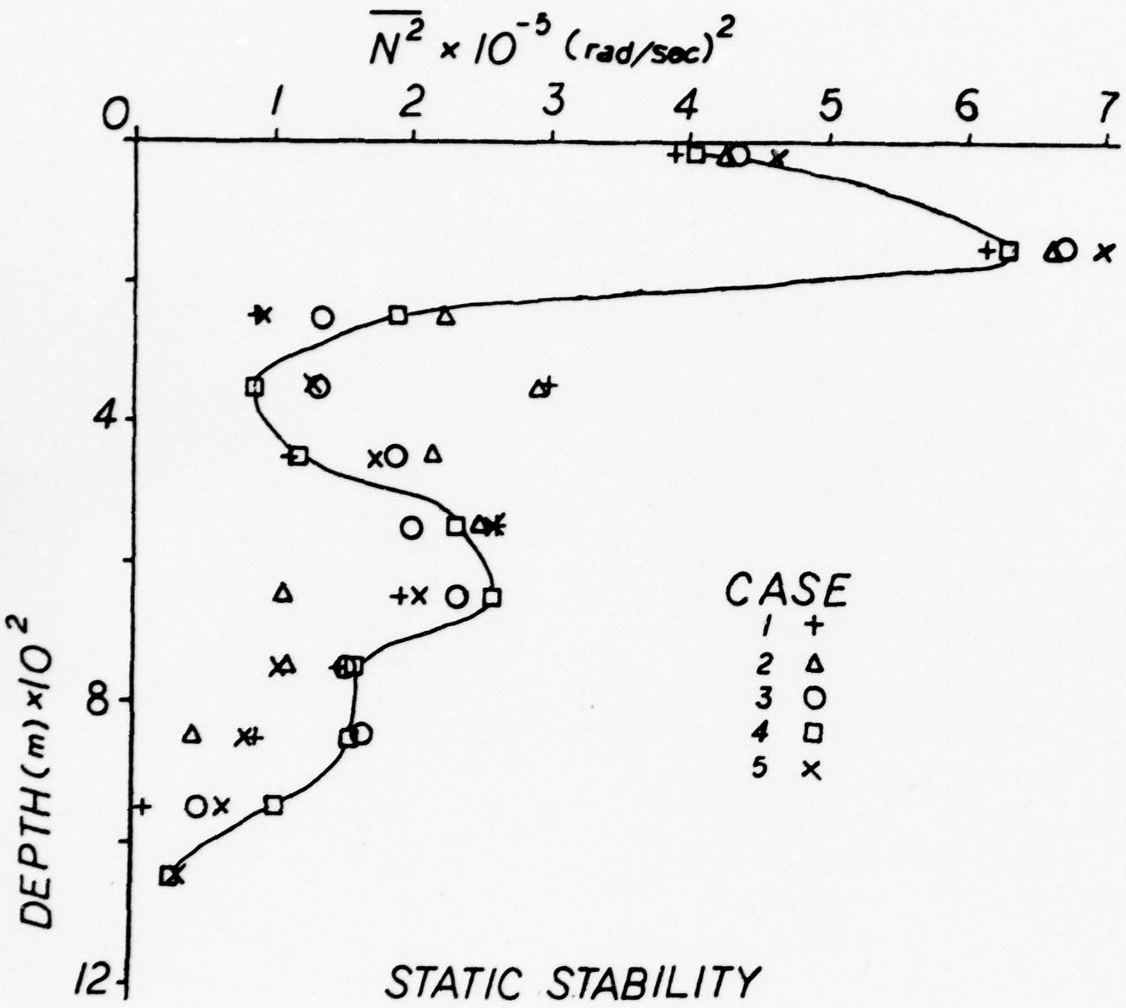
12-15
16-20
21-25

Fig. 3


$\overline{N^2} \times 10^{-5}$ (rad/sec)^2
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STATIC STABILITY

Fig. 4

4.0 Methodology Used to Compute Internal Wave Mode Shapes

Using the computed N^2 profiles presented in the previous section Eq. (8) was solved numerically to yield the vertical displacement eigenfunctions for the internal (baroclinic) modes. The following presents the description of the methodology.

4.1 Method Description by J. Doubek

We have the equation (from Section 2.0)

$$\frac{d^2 w}{d z^2} + k^2 \left(\frac{N^2(z) - \sigma^2}{\sigma^2 - f^2} \right) w(z) = 0 \tag{8}$$

where z is depth, $N^2(z)$ the depth dependent Brunt-Väisälä frequency, f is the local inertial frequency, σ the frequency of interest and k^2 an unknown parameter (eigenvalue). Given the water depth D, the boundary conditions are as follows

$$w(0) = 0$$

$$w(D) = 0. \tag{9}$$

The above assumes $N^2 > \sigma^2 > f^2$; ie applicable to intermediate frequencies. To simplify, let

$$g(z) = \frac{N^2(z) - \sigma^2}{\sigma^2 - f^2} .$$

Then, if g(z) is twice continuously differentiable, there exists an infinite but countable number of solutions

$w_n(z)$, k_n^2

where $0 < k_1^2 < k_2 \ldots < k_n$.

To solve the boundary value problem Eq. (8) is approximated using the finite difference equation

$$D\bar{u} + \lambda^2 B\bar{u} = 0 \tag{10}$$

where D is the second order NxN finite difference operator (refer to Keller, 1968).

$$D = \begin{pmatrix} -2 & 1 & 0 & 0 & \cdot & \cdot & \cdot & & & \\ 1 & -2 & 1 & 0 & 0 & \cdot & \cdot & & & \\ 0 & 1 & -2 & 1 & 0 & \cdot & \cdot & & & \\ & & & \cdot & \cdot & \cdot & \cdot & & & \\ & & & \cdot & \cdot & \cdot & \cdot & 0 & 1 & -2 \end{pmatrix} \tag{11}$$

λ^2 is k^2 scaled by a discretization constant and B is the operator

$$B = \begin{pmatrix} g(z_1) & 0 & 0 & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & g(z_2) & & 0 & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & & g(z_3) & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & g(z_N) & \end{pmatrix} \tag{12}$$

The z_i are taken at evenly spaced mesh points $z_i = i \cdot D/(N+1)$.

Next, find a vector $\bar{u}$ where

$$\bar{u} = \begin{pmatrix} u(z_1) \\ \cdot \\ \cdot \\ u(z_N) \end{pmatrix} \tag{13}$$

Then $\overline{u}_n$ will be an approximation to the desired eigenfunction w_n.

Eq. (10) can be rewritten as

$$B^{-1}D\,\overline{u} + \lambda^2\,\overline{u} = 0 \tag{14}$$

and notice that (14) is now just a matrix eigenvalue problem.

Rewriting agan, we have

$$-B^{-1}\,D\,\overline{u} = \lambda^2\,\overline{u} \tag{15}$$

and letting $A = -B^{-1}D$ Eq. (15) becomes

$$A\,\overline{u} = \lambda^2\,\overline{u} \tag{16}$$

where

$$A = \begin{pmatrix} \frac{2}{g(z_1)} & -\frac{1}{g(z_1)} & 0 & \cdot & \cdot & \cdot & \cdot \\ -\frac{1}{g(z_2)} & \frac{2}{g(z_2)} & -\frac{1}{g(z_2)} & 0 & \cdot & \cdot & \cdot \\ 0 & -\frac{1}{g(z_3)} & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & -\frac{1}{g(z_N)} & \frac{2}{g(z_N)} \end{pmatrix} \tag{17}$$

Next Eq. (16) is solved numerically. Fortunately A is of simple form such that the solution of the equation

$$\det\,(A - \lambda^2 I) = 0 \tag{18}$$

is greatly simplified. In fact, for an arbitrary x, det(A-xI) can be evaluated in only about 3N operations, using a simple recursion formula (refer to Dahlquist and Bjorck, 1970).

Using bisection followed by the secant method, the first five roots of (18) can usually be found using less than a minute of computing time.

The equation

$$(A - \lambda_i^2 \; I) \; \bar{u}_i = 0 \tag{19}$$

is then solved for $i = 1,2,\ldots5$. Since $\det(A - \lambda_i^2 \; I)=0$ (i.e. λ^2 is an eigenvalue), the solution (19) is not determined; however by setting

$$u_i(z_N) = 1/N \tag{20}$$

the remainder of the eigenvector $\bar{u}_i$ is uniquely determined. It should be noted that (20) is necessary because, in fact, the w_n of the original equation are unique only up to a multiplicative constant.

5.0 Mode Shape Perturbations

This study examines only the semi-diurnal tidal component of the internal wave field. As discussed earlier in this report the semi-diurnal component is the most energetic high frequency signal seen in the data (Fig. 2). The analyses of the vertical structure to follow were computed using the averaged Brunt-Väisälä profiles (refer to Table 2 and Fig. 4, Section 3.0) via the numerical method as given in Section 4.0.

When viewing the results to follow the reader should bear in mind the following.

1. By convention the modes were plotted in such a manner that the first maximum (nearest the surface) is always positive.
2. The vertical displacement is normalized to 1.0. For this study no energy mapping onto the modes was done. As such it is not possible at this time to assign the energy distribution by mode. From a cursory examination of the data it is felt, however, that because of the proximity to the continental shelf the lower order modes will dominate.
3. Only the first three modes are plotted. This is done partly for clarity and also because of the assumption of lower order mode dominance.

Figs. 5 through 9 present the mode structure for the five cases. To reiterate the cases are as follows.

1. Case 1 - period of onset of the meso-scale event.
2. Case 2 - period of greatest perturbing by the event.
3. Case 3 - period of passage.
4. Case 4 - quiescent period; no observable meso-scale feature.
5. Case 5 - minor perturbation but no indication of a meso-scale event.

In order to better examine the effect of the meso-scale feature the individual modes were compared to the quiescent case 4. Case 5 was not used in this comparison. Figs. 10 through 12 present the comparisons of modes 1, 2, and 3, respectively. The results are summarized as follows.

For mode 1 the level of maximum surfaces by of the order of 200 m during the period of greatest meso-scale perturbing. This is of particular importance in that the region of maximum occurs near the zone of the sound speed minimum. The maxima level change in the mode 2 cases also occurs in the region of the sound speed minimum. However, the perturbing effect is much greater; maxima surfacing by the order of 500 m. For the surface maximum there is no apparent level change but the amplitude of the maximum changes by approximately 25%. Again in the mode 3 comparisons there exist amplitude and level changes of the same order of magnitude.

In terms of the effects of these perturbations on the acoustic field the relationship is not completely known. First, as pointed out by Mooers (1975) the only simple

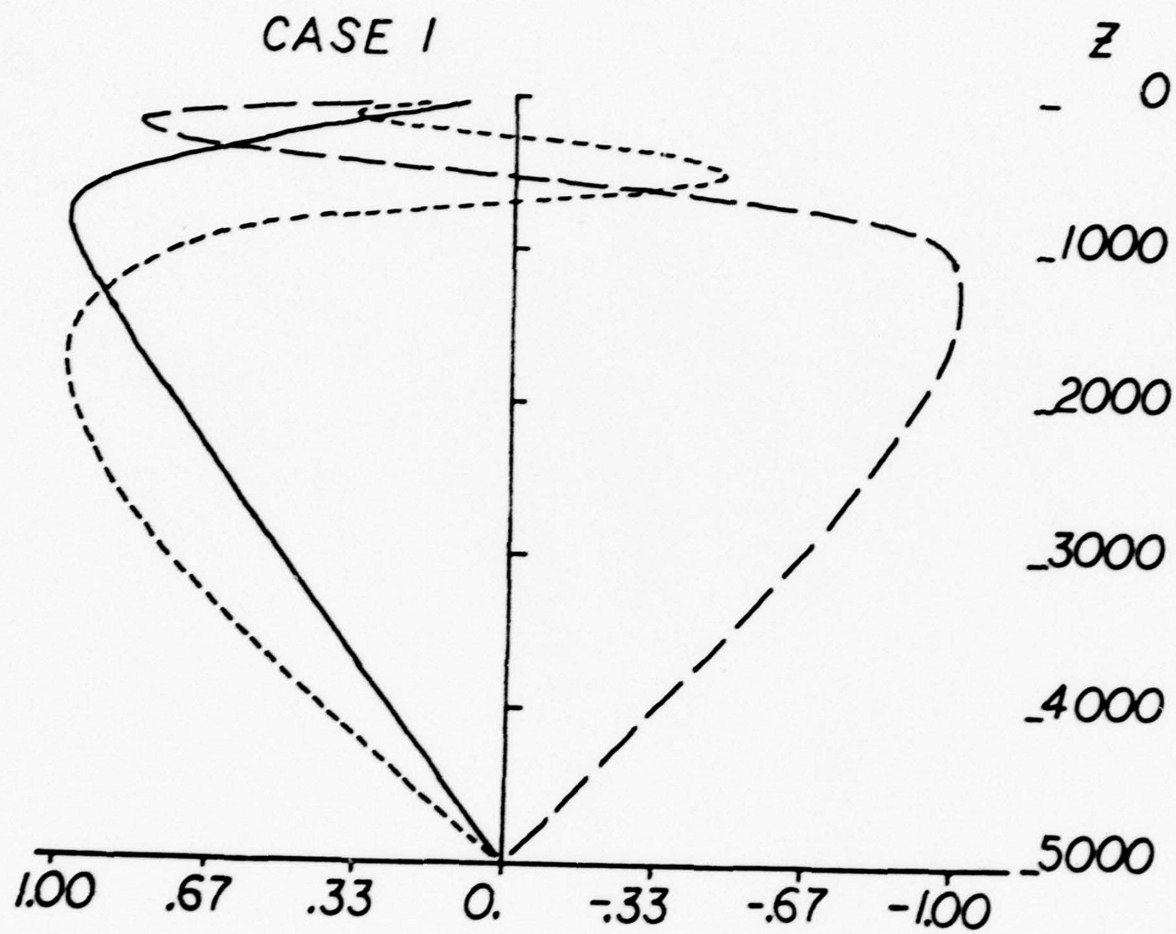

Fig. 5 Mode Structure: Case 1

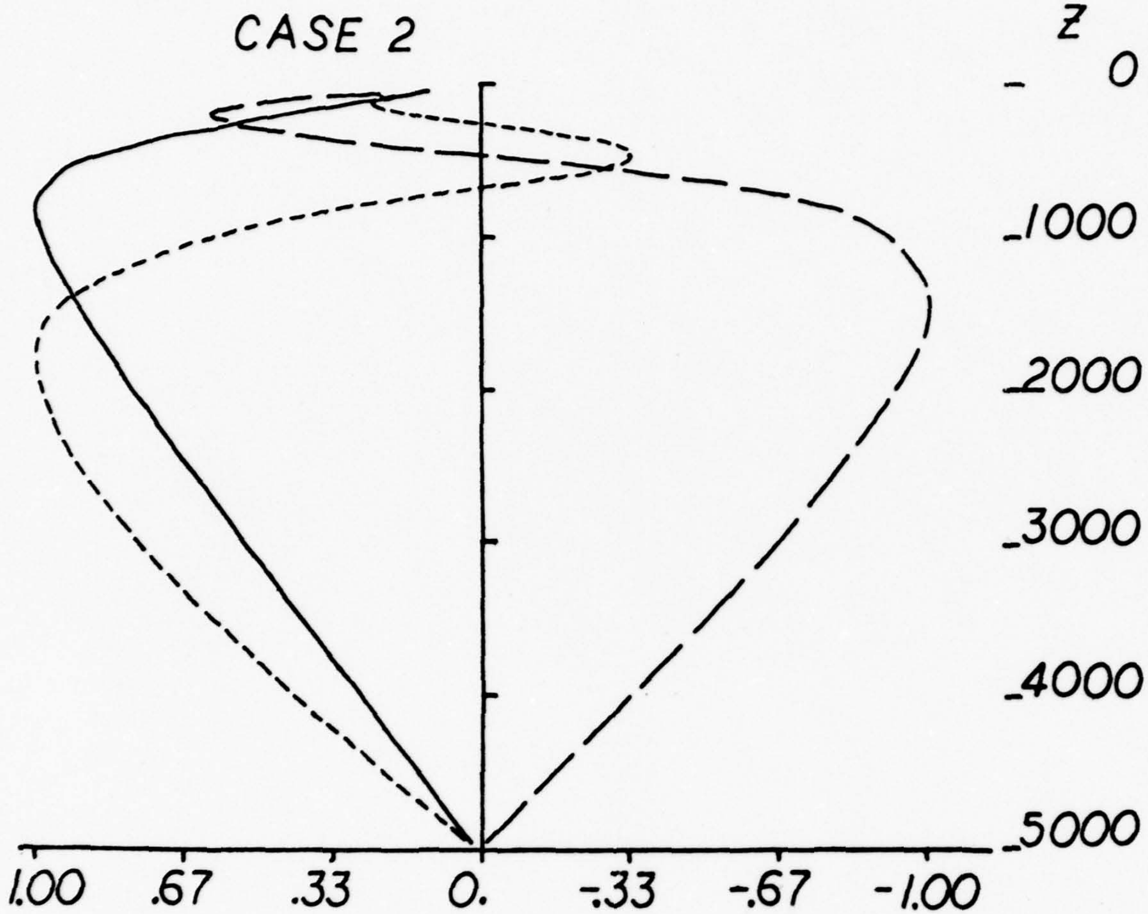

Fig. 6 Mode Structure: Case 2

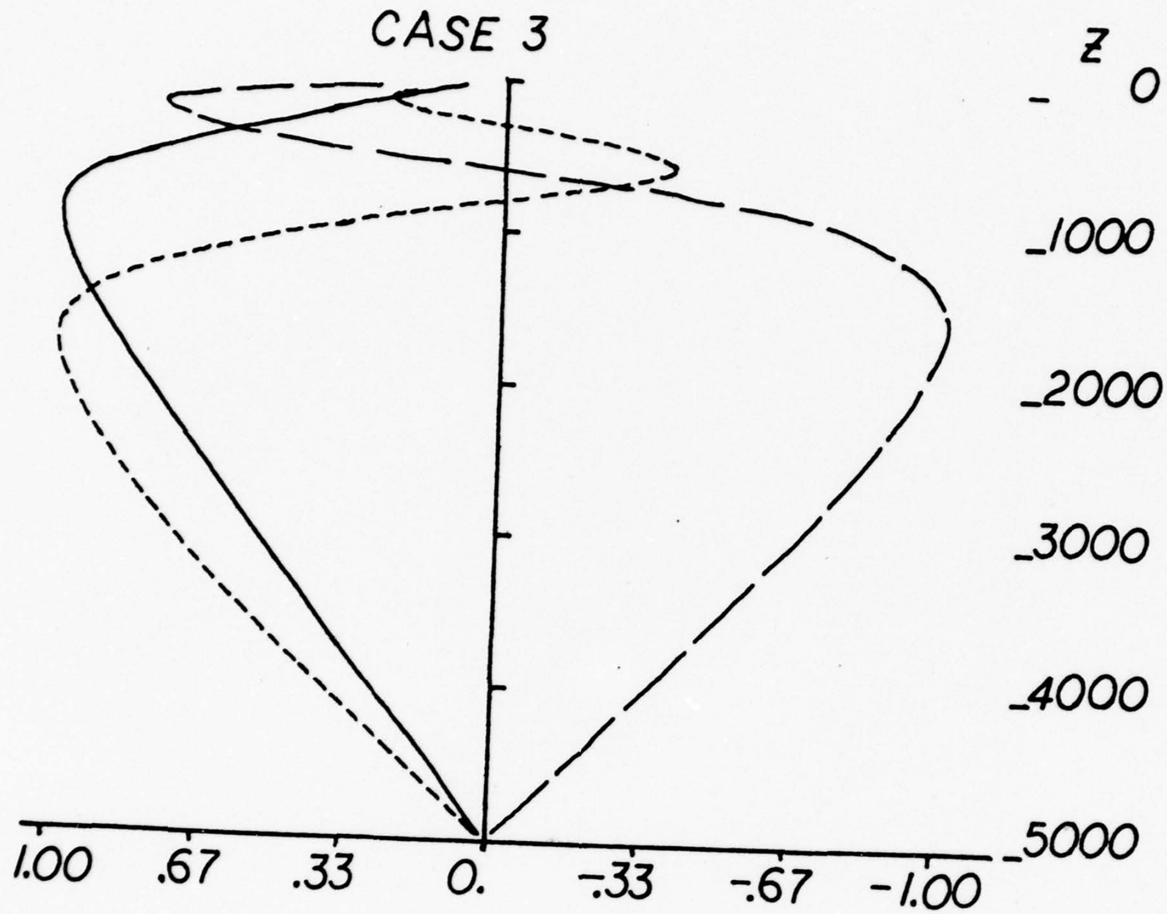

Fig. 7 Mode Structure: Case 3

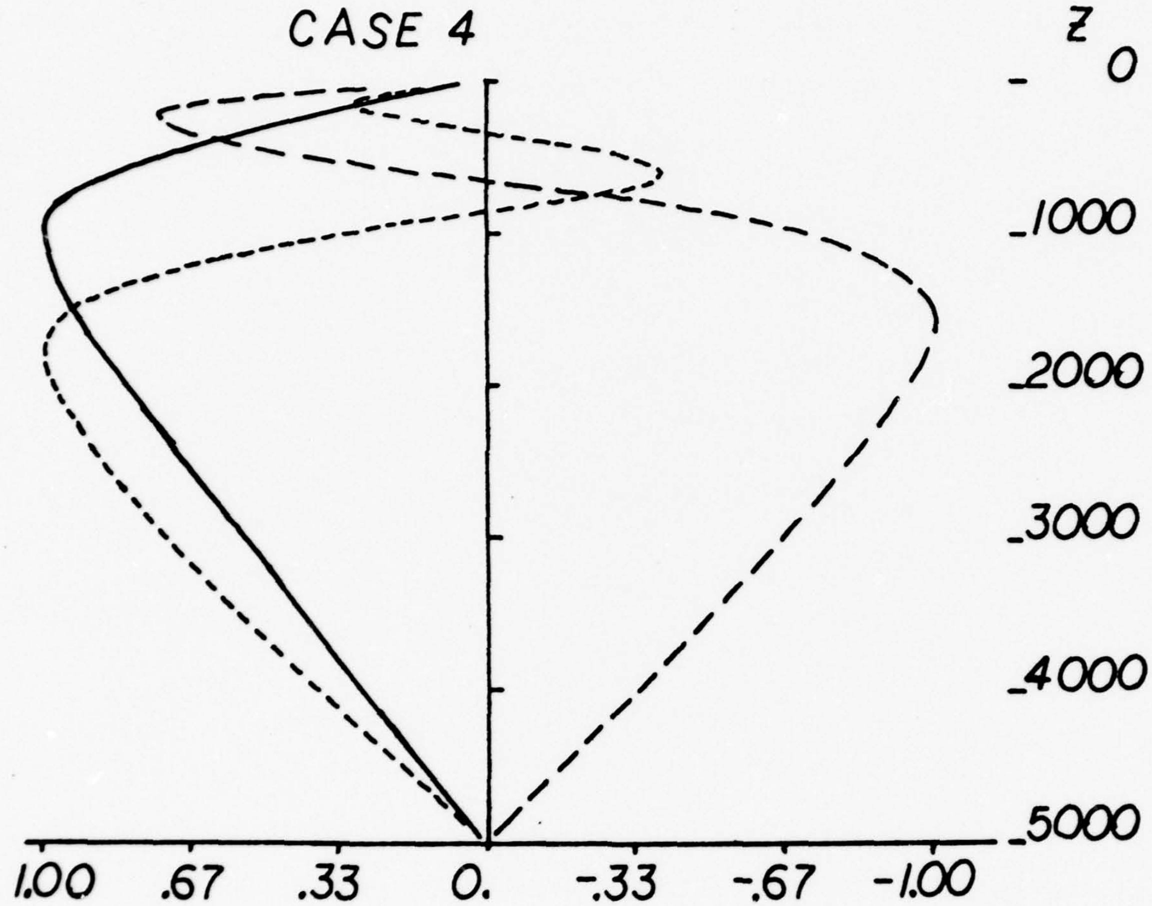

Fig. 8 Mode Structure: Case 4

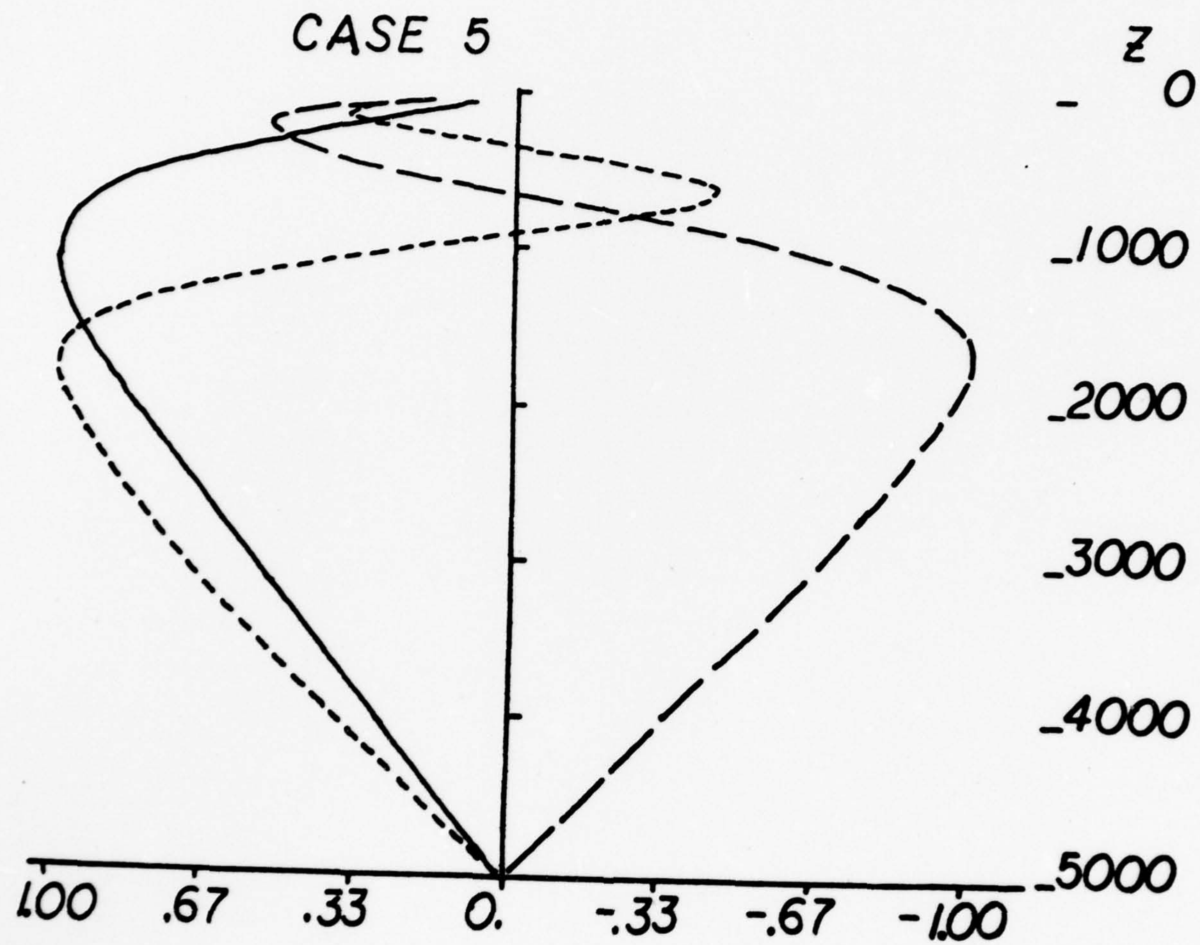

Fig. 9 Mode Structure: Case 5

relationship between a given mode structure and the corresponding sound speed anomaly is the depth of the zero crossings. Thus for the higher order modes the changes in level of the zero crossings (refer to the mode 2 and 3 cases, Figs. 11 and 12) will contribute to as yet unknown perturbations in the sound speed anomalies. Secondly, in general, variations in the depth of the SOFAR axis occur in response to and are approximately equal to the maximum amplitude of the first mode. However, the effect of the level change on SOFAR axis variations is new question.

Before the results of this study can be used to address the above questions the following must be done. The energy mapping onto mode must be done for the four cases; ie determine the energy partitioning. Once known it is then possible to examine the interference patterns in the sound speed anomalies and determine the effect of the meso-scale event.

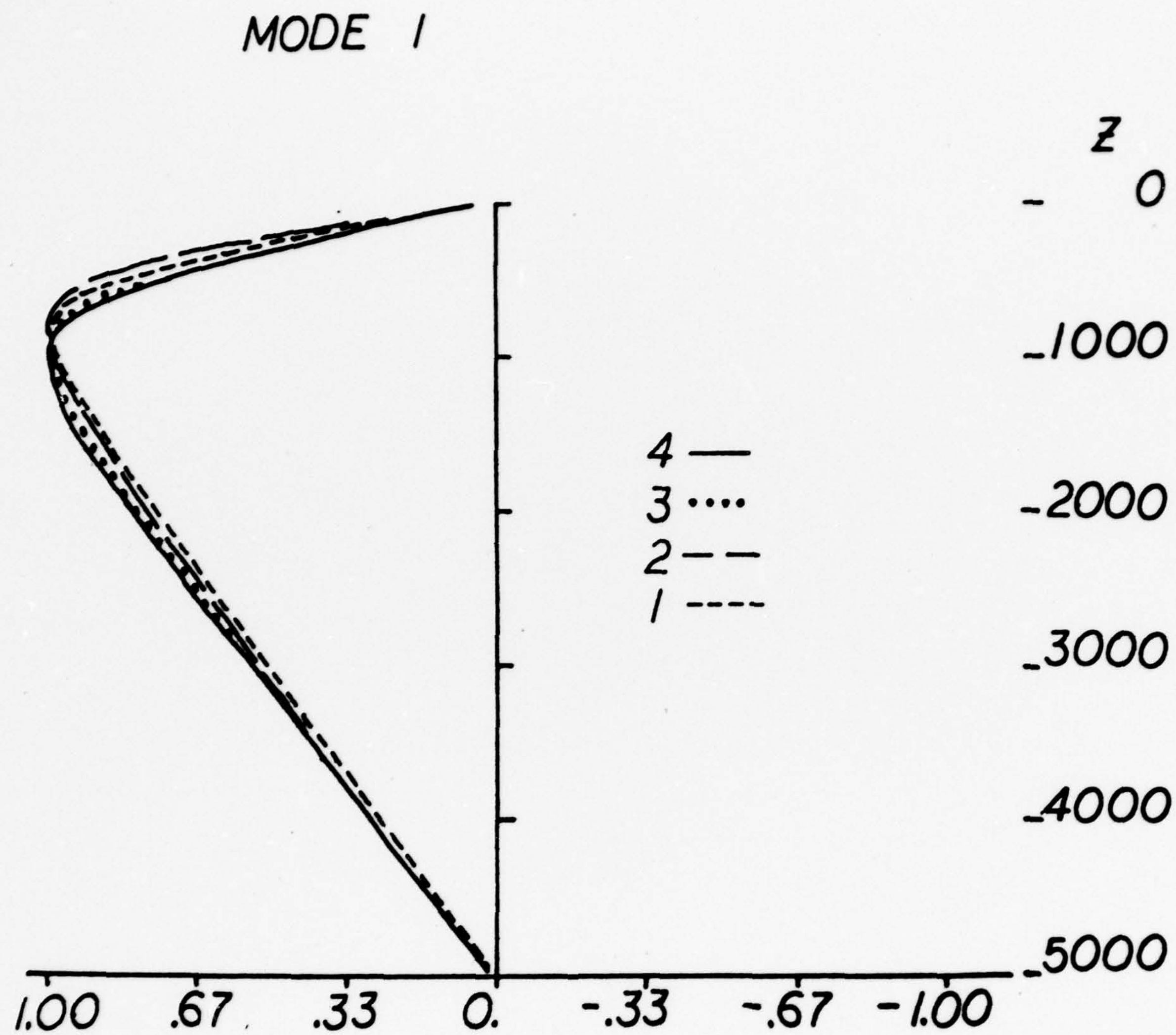

Fig. 10 Structure Comparison of Mode 1

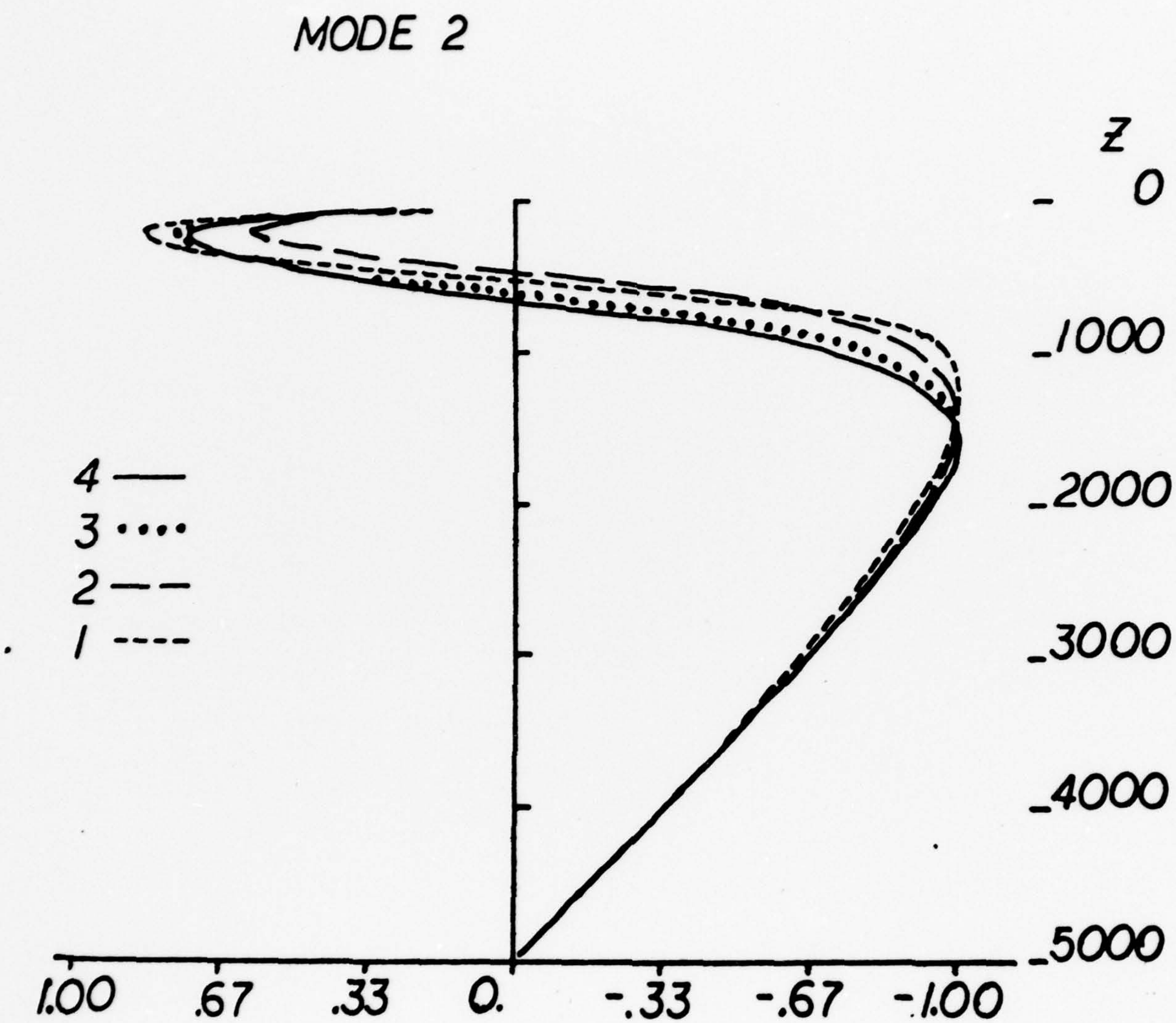

Fig. 11 Structure Comparison of Mode 2

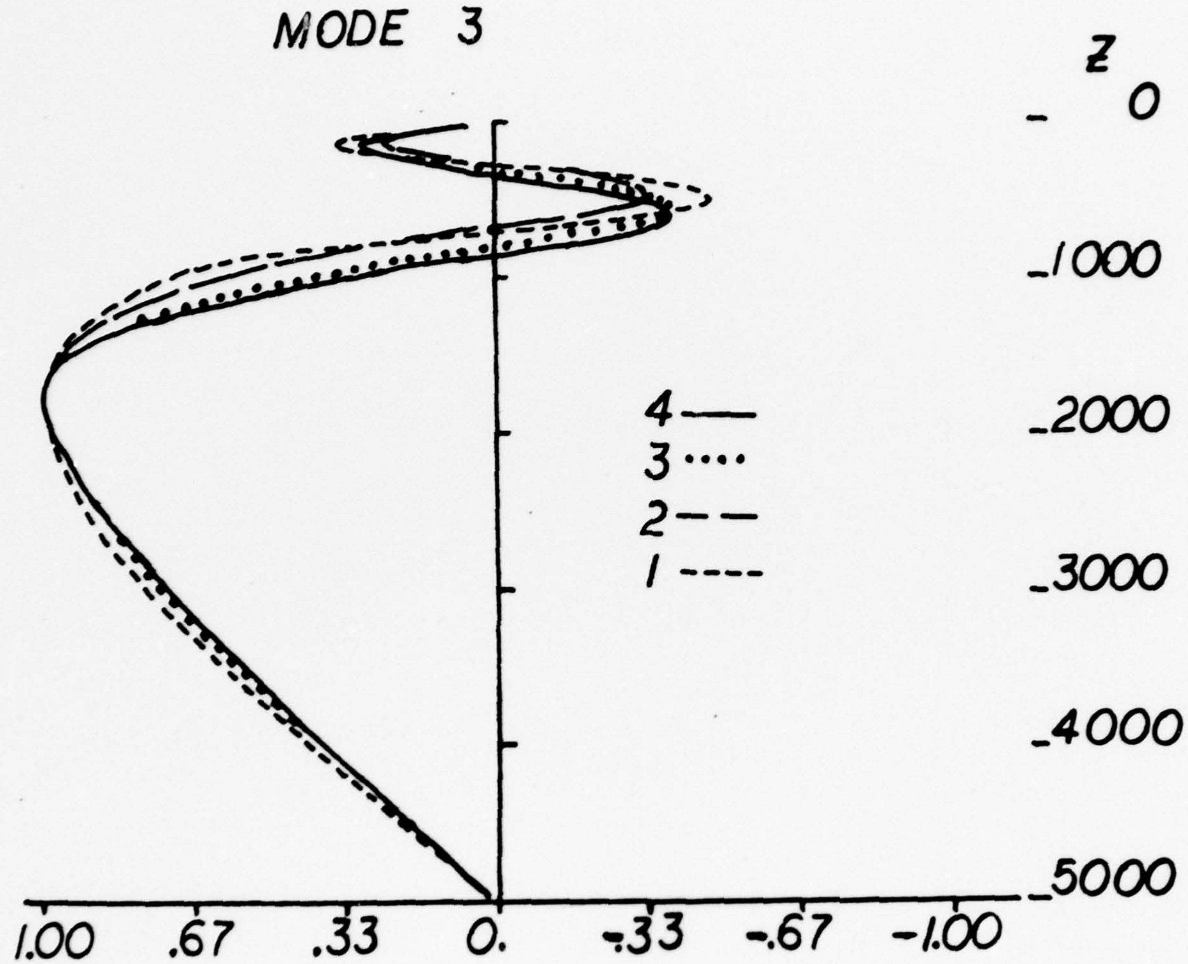

Fig. 12 Structure Comparison of Mode 3

6.0 Discussion

This study has presented changes in the vertical structure of the semi-diurnal tidal component of the internal wave field. The perturbations were associated with the passage of a meso-scale feature through the study region.

The results of this study have shown that the meso-scale feature had a decided influence on both the depth location and the amplitude of the maxima of the vertical displacement. These results are not surprising in that the amplitude and location of maxima are functions of the static stability. However, this reports documents, for the first time, this effect. The impact of these results is the magnitude of the perturbation on the mode structure. It should be remembered that the feature observed in these data was an edge effect. Thus much larger perturbations in the structure would be expected in the center of such a feature. Obviously these perturbations, considering the time scale, will have a direct effect on the acoustic path structure. But it should be emphasized that the acoustic problem cannot be treated until the total energy is partitioned by mode. Once that step is taken it is then possible to relate, in a quantitative manner, the effects of meso-scale features on the acoustic field.

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This study examines, in detail, the effect of the passage of a meso-scale feature through an area normally under the influence of the Antilles Current. The study area lies approximately 40 km northeast of the island of Eleuthera, Bahamas. The analyses examine, in particular, changes in structure of the vertical displacements of the semi-diurnal tidal component of the internal wave field. The report also includes a description of the

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methodology used to compute the vertical displacements.